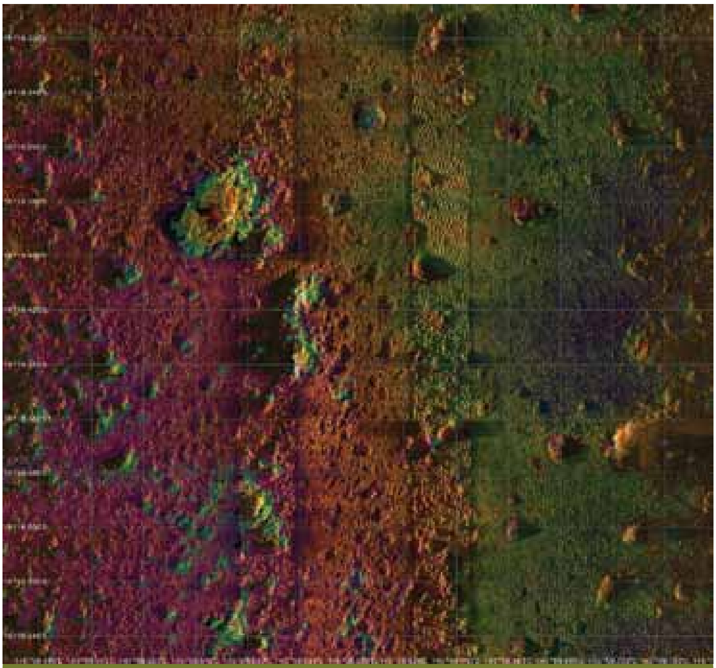

A New Approach to High-Resolution Seafloor Mapping

by Hayden John Callow, Per Espen Hagen, Roy Edgar Hansen, Torstein Olsmo Sæbø, and Rolf B. Pedersen

Introduction

High quality, accurate maps of the seafloor are essential in a number of fields, including inspection of oil and gas installations and underwater cables and pipelines, fisheries and marine habitat monitoring, and environmental compliance testing.

When mapping the seafloor, two considerations are important – the ability to discriminate fine features (spatial resolution) and the ability to cover as much area as possible with a single pass (wide swath). Side scan sonar has long been valued for its ability to cover wide swaths of seafloor with a single pass. However, there is an inverse relationship between the frequency of the sonar and its spatial resolution – lower frequency sonars achieve wide swath coverage, but at lower spatial resolution. As a result, conventional side scan sonars offer high-resolution or high area coverage rates, but not both at the same time.

Synthetic aperture sonar (SAS) uses sophisticated processing of the sonar signals to produce a very narrow effective beam (i.e., high-resolution). SAS uses software to combine many single pings from a moving platform to synthesize a long sonar transducer, up to many tens of metres in length. This longer effective sonar allows for high-resolution imagery at lower frequencies than possible with a conventional side scan sonar with the same resolution. In turn, lower frequencies make imaging possible at longer range, giving a higher mapping rate.

As an active remote sensing system, both the amplitude (and hence frequency/wavelength) and phase of the outgoing acoustic signal are well known for all side scan sonars. Most applications of side scan sonar make use of the amplitude of the return signal to determine variations in the texture of the seafloor, but ignore the phase data. Interferometry uses the phase of the reflected signal to extract other characteristics of the seafloor – in particular, variations in elevation. Since the phase of the outgoing signal is known, it can be compared to the phase of the return signal. Since the path length to the seabed and back will consist of a number of whole wavelengths plus some fraction of a wavelength, the phase difference or phase shift between the outgoing and returning wave can be used to infer the path length. By comparing the phase shift for two separate observations of the same area of seafloor taken from slightly different positions, the height of the seafloor may be calculated.

Interferometric synthetic aperture sonar combines interferometry with the benefits of aperture synthesis to give a five to 10 times improvement in bathymetric mapping efficiency over conventional side scan sonars and multibeam echo sounders (MBES) at similar resolutions. Interferometric SAS is a relatively new technology and is only just now reaching maturity. This essay describes the technology behind an interferometric synthetic aperture sonar with particular reference to the HISAS 1030 system developed by Kongsberg Maritime. We outline some of the sonar design and data processing challenges, explain how we have addressed the challenge of filling the 'nadir gap,' and highlight the upside of deploying SAS sensors on AUV-based survey vehicles.

Interferometric Synthetic Aperture Sonar

Interferometric synthetic aperture sonar systems improve mapping efficiency by generating very high-resolution seafloor images and high-resolution bathymetric measurements over a wide swath. In addition, both the imagery and bathymetry have range-independent spatial resolution, allowing high quality over the entire swath. A high-performance sonar system such as the HISAS 1030 has a maximum bathymetric grid resolution of 10 cm x 10 cm and is able to map at up to 2 km^2 per hour. The high spatial resolution allows fine seafloor textures to be resolved. This aids in seafloor classification and can prevent costly mistakes in other applications of seafloor mapping – avoiding the need for time-consuming re-inspection of areas of interest using other survey methods. The very high image resolution available when using SAS systems opens up entirely new application areas for seafloor mapping.

Synthetic aperture sonar (SAS) uses many pings to emulate a longer sonar, increasing spatial resolution without needing to increase operating frequency. By lengthening the synthetic aperture as range increases, image resolution can be kept constant. In effect, SAS uses software and processing to replace costly and unwieldy sonar hardware. The main benefits of this approach are high spatial resolution that is frequency and range independent, and wide swath coverage (Figure 1).

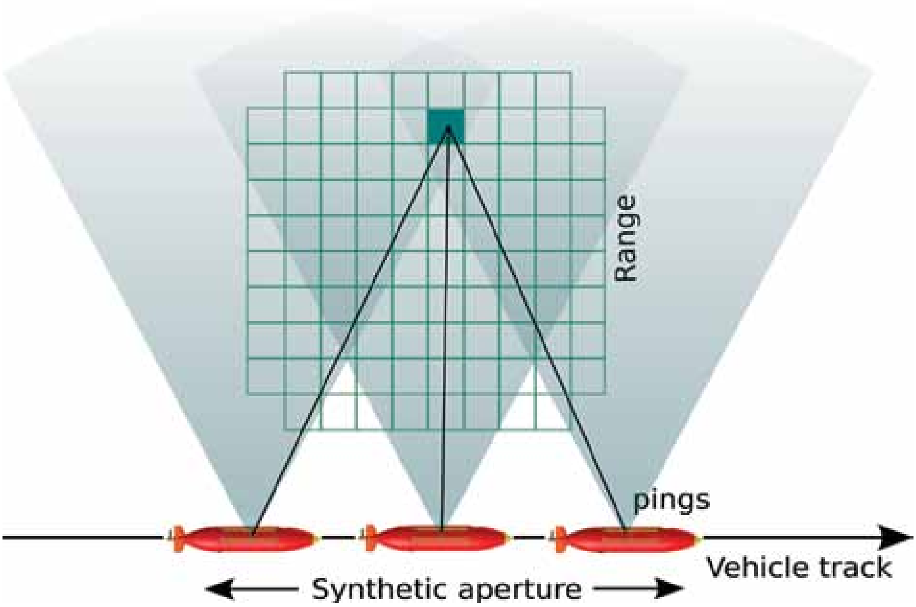

Figure 1: Synthetic aperture sonar imaging concept. Because of the wide transmit and receive beams, each section of the seafloor is ensonified by a number of consecutive pings as the platform travels past the scene.

One interesting side effect of using SAS is that robust SAS requires bathymetry at resolutions roughly comparable to that produced by a multibeam echo sounder (MBES); this can be generated from real-aperture (single ping) sonar data from multiple, vertically displaced receiver antennas. Each antenna receives echoes from the same part of the scene at slightly different times, and these differences can be estimated through a comparison of the received signals. This can be done either using cross-correlation techniques, or through phase differencing. A difference in arrival time is related to the depression angle of the incoming signal. Combining the depression angle with the time between the transmission and reception provides an estimate of the vertical position of the target. The along-track resolution of the real-aperture depth estimates is determined by the resolution of the real-aperture imagery. However, once SAS imagery is formed from each of the interferometric arrays, the same method can be applied to generate high-resolution interferometric height maps. As the input imagery has the range-independent resolution that SAS provides, so does the depth estimate grid (Figure 2).

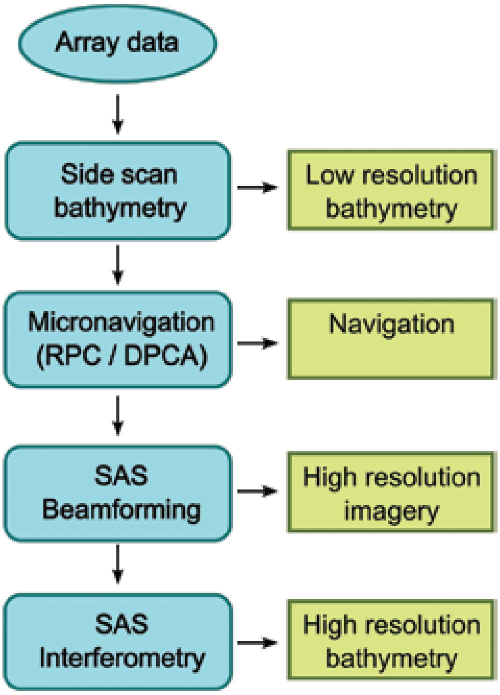

Figure 2: Illustration of SAS processing flow chain. Early estimates of coarse bathymetry are used as inputs to SAS image formation.

Given that the depth estimate grid size is constant for all ranges, it is difficult to discuss the resolution of interferometric SAS systems in terms of effective beam-width – the typical measure of MBES and side scan sonar resolution. For HISAS 1030, bathymetric resolution matches that of a high-resolution (0.5° beam) MBES at about 10 m range – and maintains the same constant high-resolution over its entire 200 metre-per-side swath width.

Challenges

Generating bathymetric estimates from SAS imagery is more or less the same as when generating them in standard interferometric side scan sonars, and is similar to the methods used in MBES at low grazing angles. The main differences are caused by churning the imagery through a SAS processor.

This can introduce some challenges:

- SAS image artifacts, in particular grating lobes (due to spatial undersampling or imperfect motion compensation), can cause loss of accuracy and give incorrect height estimates where they occur. So platform stability, and the SAS processor's ability to estimate and correct for instability (already an issue for conventional high-resolution sonar systems), is even more important for height mapping applications.
- Numerical accuracy needs to be high. A number of typical shortcuts taken in SAS processors to reduce computational costs can introduce errors of such a magnitude that height map accuracy suffers.
- Traditional motion compensation used for correcting MBES measurements does not work. Because multiple pings make up every pixel in SAS bathymetry data, either the SAS processor must apply any improved navigation processing to each ping, or bathymetric post-processing software must be adapted to support the type of data that interferometric SAS produces.

Once these issues are cared for, relative height accuracies for SAS systems are in principle similar to those for traditional interferometric side scan sonar systems. However, to generate better height estimates, the processor averages the height estimates from many pixels. This gives bathymetry output on a lower resolution grid than the original SAS imagery, but at much improved accuracy. The averaging leverages the wide bandwidth available in high-end SAS systems and, in effect, replicates some of the benefits of vertical arrays seen in other interferometric side scan sonar systems. As always, there is a tradeoff between the number of pixels averaged, the output resolution and the signal to noise ratio (SNR).

We have designed the HISAS 1030 to have about a 5 cm standard deviation in height estimates on a 10 x 10 cm bathymetric grid for typical seafloor SNRs at 100 m range. At this accuracy, it is straightforward to observe low amplitude sand-ripples and various types of seafloor fauna. Objects with a stronger scattering response, pipelines and cables for example, give even better height estimates due to the increased SNR.

Unlike seafloor grid resolution, SAS bathymetry height estimates have varying accuracy as a function of range. Accuracy is proportional to the array separation and worsens approximately linearly with range to the seafloor. Increasing either the SNR or the distance between interferometric arrays improves accuracy. The upshot of this is that reduction of the SNR or array distance requires averaging of extra pixels to make up the accuracy. Perhaps the best method of improving height accuracy is in increasing the bandwidth of the sonar, thus increasing the number of pixels, and in addition helping to reduce the effect of interferometric ambiguities.

Interferometric SAS systems can suffer from ambiguous height estimates. This is equivalent to phase unwrapping ambiguities seen in interferometric side scan sonar systems. The height ambiguity location is dependent on the sonar's operating frequency and the distance between the interferometric arrays (baseline). Use of small baselines and lower frequencies, along with using large bandwidths compared to the sonar centre frequency, all help in reducing or eliminating this issue. The reason increased bandwidth helps is that the ambiguous estimates appear at slightly different heights at different frequencies – due to each frequency having a different wavelength. This allows the various ambiguities to be partially resolved as the bandwidth increases, making the true sea floor height the most likely choice.

The HISAS 1030 design follows these guidelines, using a large relative bandwidth and medium sized array displacement. In addition, the FOCUS SAS processor, which generates SAS bathymetry from HISAS data, employs a two-step process to further reduce the likelihood of ambiguous estimates. Currently, it employs an iterative combination of different algorithms where a robust method bootstraps a fine, high-resolution local estimation method. At the moment, the system works well on seafloors of up to moderate complexity but is not very robust on shipwrecks and other large man-made structures.

Part of the answer to solving the robust SAS bathymetry problem has been developed at the Norwegian Defence Research Establishment through the use of split-frequency interferometry techniques in the FOCUS SAS processor. With these methods, the bandwidth is divided up into sub-bands and an interferogram generated from each. The phase-wrap ambiguity locations then appear at different heights for each sub-band, thus allowing the correct height to be chosen, as it is the same for all sub-bands. The method appears to work well for the HISAS 1030 where 30 kHz of bandwidth at 100 kHz provides enough frequency diversity that the ambiguities are removed.

The last cause of difficulty for interferometric systems is in dealing with objects that have multiple heights or scattering points in the same range-slice. This is often seen in imaging pier-supports and other vertical structures. With two narrow-band receiver arrays, only one direction of arrival is resolvable without adding extra information. The problem is difficult to solve without resorting to multiple arrays. Combining estimates over an area and including backscatter information, however, may provide part of the answer. In the fashion of the split frequency methods that solved the phase ambiguity problem, bandwidth may be used in a similar way to identify the multiple heights. Bandwidth and area averaging are thus used essentially to solve problems normally regarded as requiring multiple sonar arrays to solve.

Otherwise, bias terms and other sources of constant bathymetric estimate inaccuracy are, with a few complicating factors, the same as for other mapping systems with a similar horizontal geometry. To obtain the best performance from the sensor, roll measurements must be accurate and sound speed profile ray-tracing performed. The complicating factor involved when using SAS imagery is that there is no longer a single transmitter location or a single ping to roll compensate. SAS processing chains create each pixel by blending many pings – sometimes hundreds. Fixing this requires that the SAS processing chain itself perform motion compensation. Typically, SAS chains do this anyway and the only practical cost is in a change to the normal bathymetric workflow. Motion compensation of SAS bathymetry outside of the SAS processing chain is unlikely to work well, if at all.

Filling the Gap

Side scan and synthetic aperture imaging deteriorates near the vertical, mainly because the geometric principle of side scan imaging breaks down as the depression angle increases towards 90 degrees. This effect is even more pronounced for SAS interferometry. The result is that interferometric SAS systems like HISAS 1030 have a nadir gap of approximately twice the altitude above the seafloor.

The standard solution to this is to run pairs of lines with partly overlapping coverage. However, if a gap filler sensor can be added, the overall system area coverage rate can typically be increased by as much as 40%. The main challenge is then to find a gap filler sensor that can provide data at a resolution matching that of the SAS.

A state-of-the-art multi-frequency multibeam echo sounder such as the Kongsberg EM 2040 has an operational altitude extending well beyond the useful HISAS mapping altitude, and it more than covers the angular sector of the HISAS nadir gap. The beam width is 0.75° x 0.75° at the highest operating frequency of 400 kHz. This provides bathymetry resolution comparable to HISAS at low altitude. For example, when operating at 15 m altitude, the EM 2040 has a beam footprint of 20 x 20 cm at 400 kHz. Intra-ping beam spacing is 11 cm, and ping spacing around 13 cm at 4 knots speed. This is comparable to HISAS bathymetry.

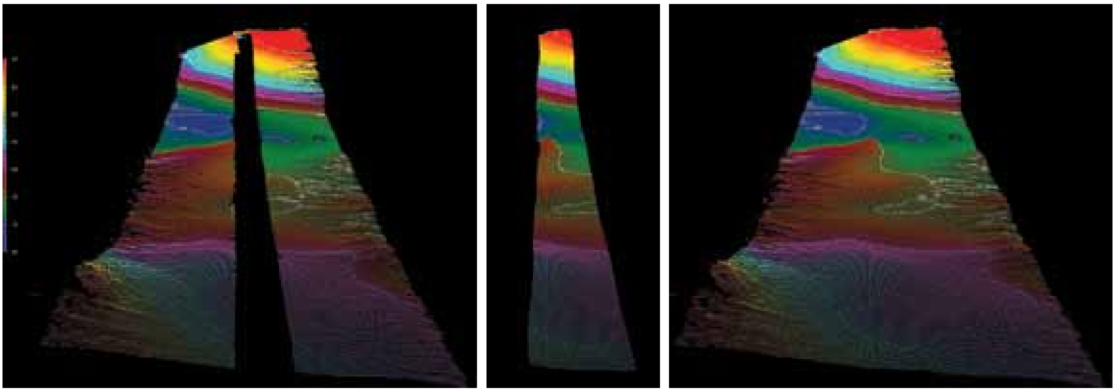

Figure 3: Combination of HISAS and multibeam echo sounder bathymetry. Left: HISAS bathymetry swath with gap around nadir; swath width 360 m. Centre: Multibeam bathymetry, swath width 70 m. Bottom: Merged bathymetry. Water depth 45-80 m, AUV altitude 20 m.

The EM 2040 has a swath width of approximately 3.5 times altitude, providing a considerable amount of overlap with the SAS bathymetry data. As the data sets are recorded with completely independent systems, at different frequencies, this allows for comprehensive quality assurance and eases any data cleaning needed (Figure 3).

Having a high-quality multibeam echo sounder like the EM 2040 also allows bathymetric mapping at even higher resolution when operating at altitudes of a few metres (e.g., for detailed imaging of small targets); and it allows wide-swath mapping at several hundred metres altitude (e.g., as a precursor survey when venturing into unknown areas); see Figure 4.

AUV-based Surveying

Thus far, this essay has primarily discussed the features and benefits of SAS imaging and bathymetric mapping in general. It is, however, important to understand that the use of a SAS system on an AUV adds a number of other advantages – some related to the platform, and some caused by the cumulative effects of the two technologies.

Firstly, a synthetic aperture sonar requires integration with an accurate aided inertial navigation system in order to determine ping-to-ping displacement in all degrees of freedom with adequate accuracy. When installed on a high-quality AUV like HUGIN, such a navigation system will already be present. Achieving precise underwater navigation requires a number of sensors and techniques, and would add substantially to the cost of a SAS system on any other platform. The core of a high-grade AUV navigation system is a survey grade (1 nmi/h class) inertial measurement unit, a Doppler velocity log for bottom and water referenced velocity measurement, and a pressure sensor to bind the depth estimate. In addition, a number of techniques are available to limit horizontal error growth – GPS positioning at the surface, ultra short baseline positioning from a surface vessel, transponder navigation (synthetic or real baseline), terrain referenced navigation, etc. In HUGIN, we also use the concept of re-navigation as a post-processing step – generating a smooth and even more accurate navigation solution for the entire mission after AUV recovery. Experience has shown that this almost always provides at least some improvement in the SAS image quality.

Another advantage of placing sensors on an AUV is that they typically operate under the surface layers, which present a notoriously difficult environment for acoustic sensing because of the near-surface sound speed variations and surface wave effects (motion). This benefit is particularly apparent when

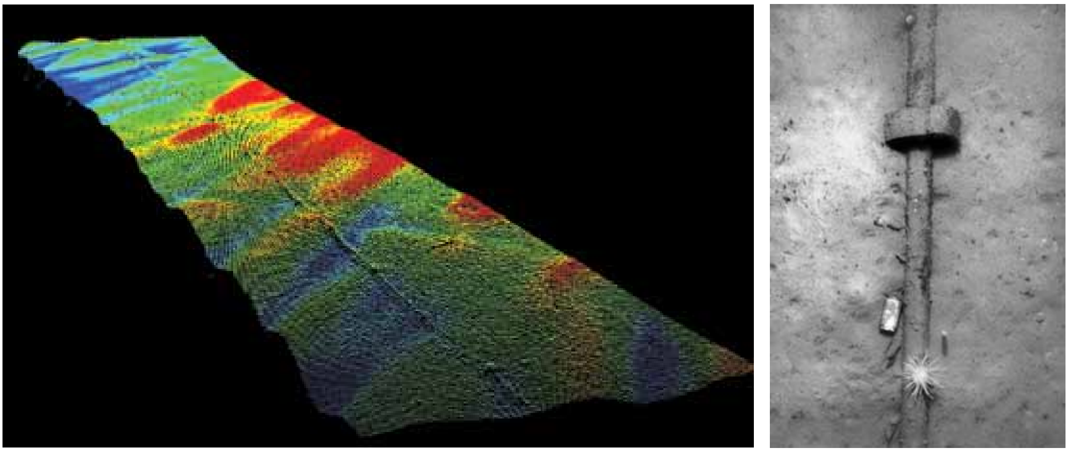

Figure 4: Example of EM 2040 bathymetry from low altitude. The left image shows a flexible cable with diameter 10 cm. Water depth 92 m, AUV altitude around 4 m. Depth colour coded with a 30 cm scale. The right image shows a camera image of the same cable (and a beer can) recorded with HUGIN in the same mission.

trying to obtain accurate bathymetric estimates in horizontal geometries.

In terms of mapping cost and efficiency, another important advantage of using an AUV as the host platform for a SAS mapping sensor is that it allows fully autonomous operations. This frees the mothership to perform other tasks, for example, mapping in another area entirely. Furthermore, even larger increases in mapping rate can be gained by deploying multiple AUVs at the same time. Thus, AUV-based sensor platforms can substantially increase the mapping rate of survey vessels, come closer to the action, and by being nearer and more stable than surface platforms produce higher resolution, higher quality maps.

Some Real World Examples of Interferometric SAS Data

There are a number of applications where the high-resolution, high mapping rates offered by SAS systems are very useful. Mine hunting is the obvious example; in fact, this application has been the main driving force behind the development of SAS: The operators need to search large areas for very small objects. The HISAS system has been used operationally in mine countermeasures for a few years. Another application where SAS is a clear candidate technology is pipeline inspection, where, for example, oil and gas transport pipes often hundreds of kilometres long, and their surroundings, must be inspected for burial, free spans, human activity, etc.

The higher resolution offered by SAS systems, particularly in combination with bathymetric mapping, provides benefits in other applications as well. This is particularly apparent in the imagery of a seafloor volcanic field presented in this essay. The detail available in the imagery gives information to geologists about the physical processes that were involved when the submarine eruptions occurred, the size of individual lava flows and the direction of flow. Besides providing unprecedented details, the SAS imagery yields an overview of the volcanic seafloor giving unique information about the architecture of the volcanic field and its eruptive history.

During this deployment, more than 5 km^2 of volcanic seafloor was surveyed in high-resolution in less than eight hours, with the entire area covered twice from different aspect directions; Figures 5 and 6.

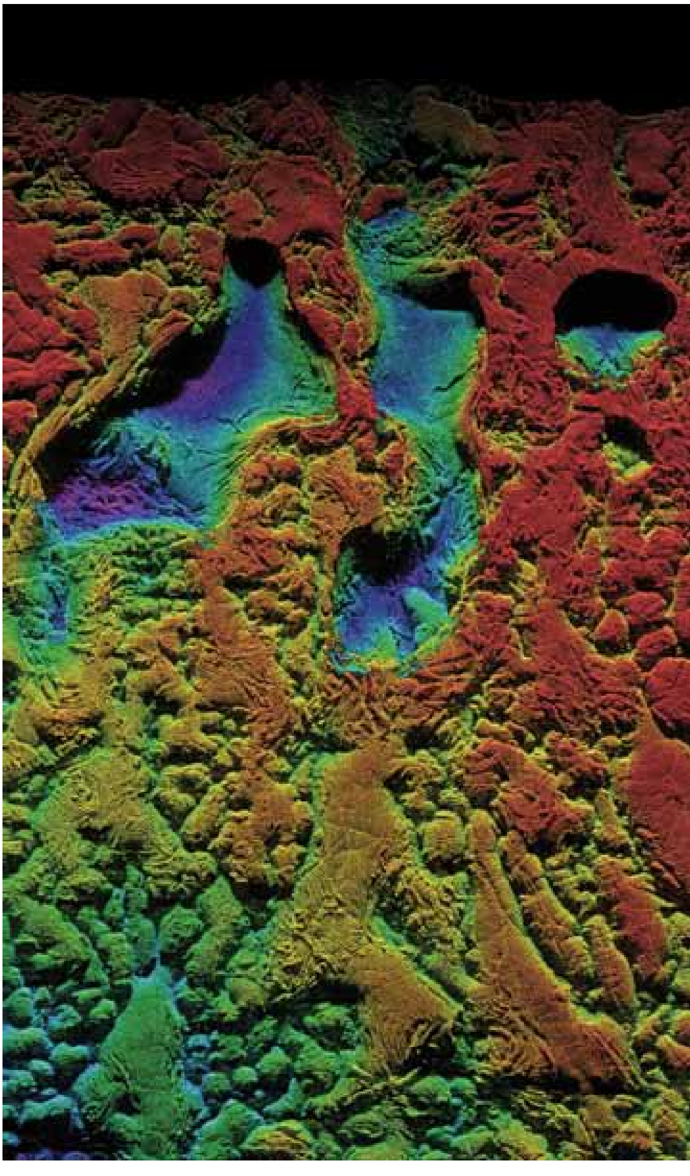

Figure 5a: Combined SAS image and SAS bathymetry of a field of pillow lava from an expedition to the Arctic Ocean in June 2011. Area 140 x 80 m, range 20-160 m, colour mapped to depth from 830.5 m to 835 m. Data used courtesy of the University of Bergen, Norway, and Norwegian Defence Research Establishment.

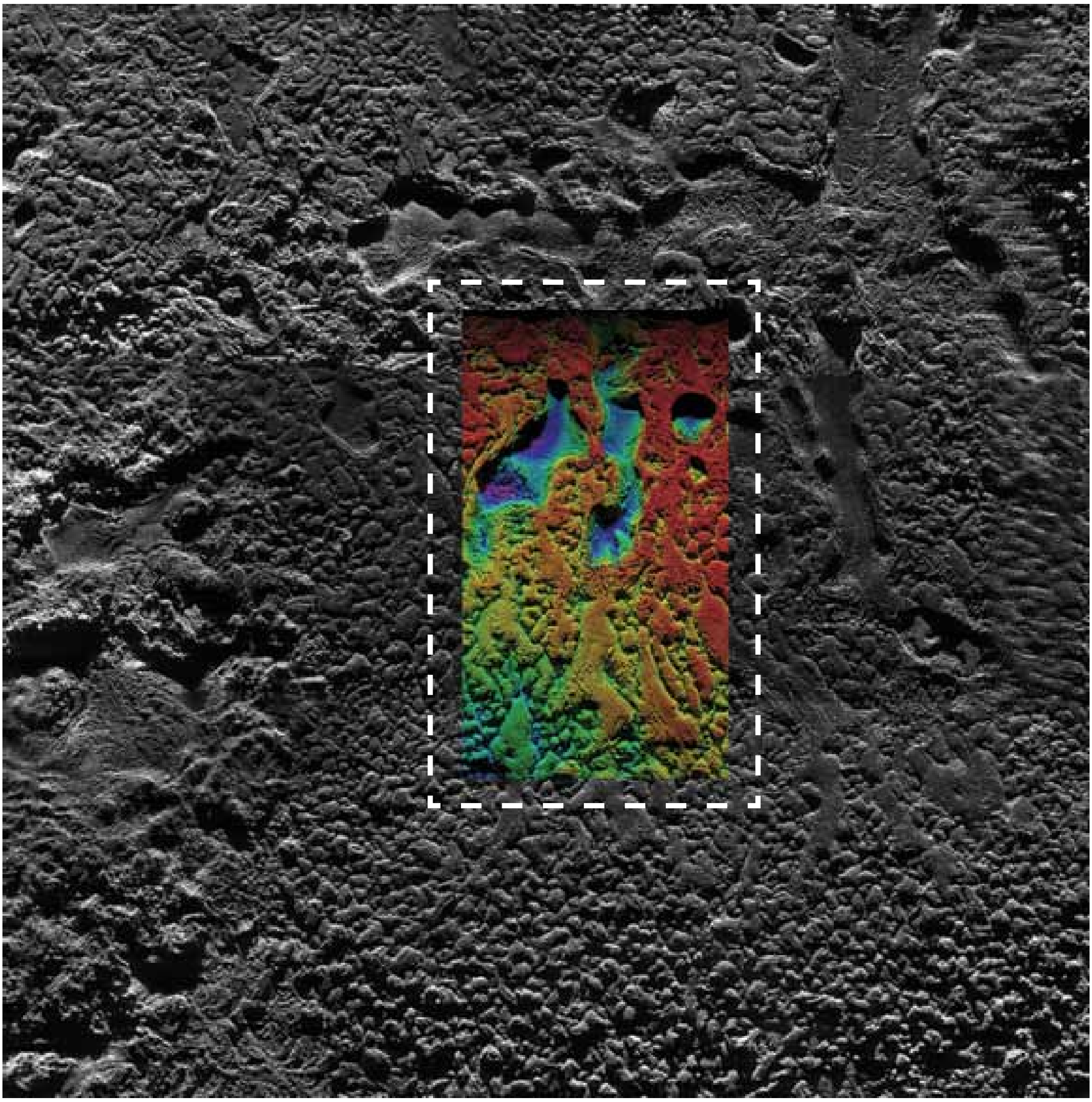

Figure 5b: 300 x 250 m excerpt from a mosaic of several SAS imaging passes over a 5.2 km^2 lava field region in the Arctic Ocean. Highlighted area in colour corresponds to pillow lava bathymetric image (Figure 5a). Data used courtesy of the University of Bergen, Norway, and Norwegian Defence Research Establishment.

Conclusion

In this essay, we have discussed how interferometric SAS systems can provide bathymetric maps at high-resolution with high mapping rates. We have illustrated the benefits of combining collocated seafloor bathymetry and high-resolution imagery and how this can improve map quality and the types of information it is possible to collect and map.

As with other uses of SAS imaging, the design of the sonar and processing chain are critical in getting robust, quality results. We have presented a number of potential issues in producing reliable maps and described how they are solved in our HISAS 1030 interferometric SAS system.

Today, standard bathymetric processing chains are not yet able to fully cater to

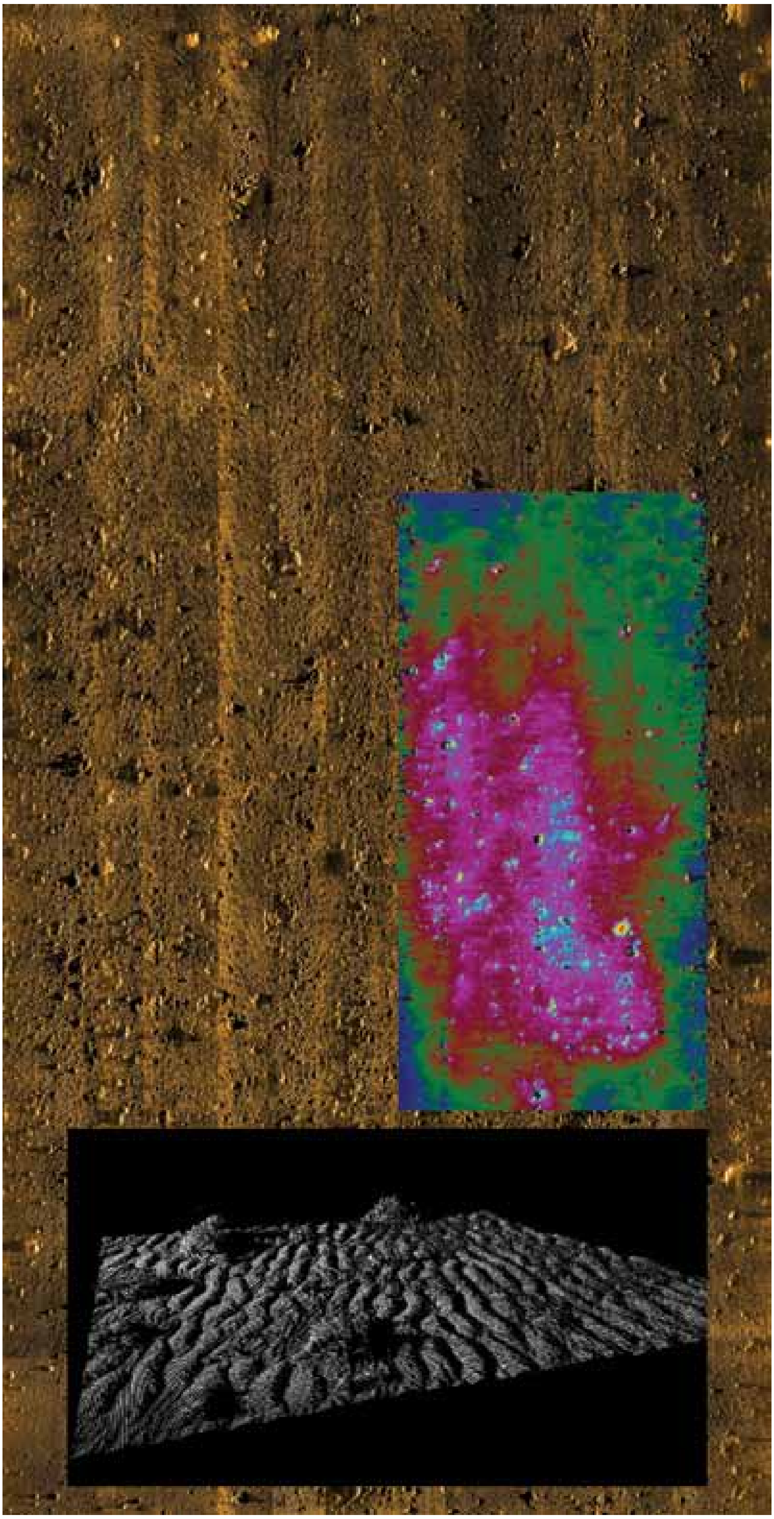

Figure 6: HISAS imagery and bathymetry from Great Barrier Reef, Australia. Inset (top): HISAS side scan bathymetry from an area of 3 km^2. Data recorded in approximately 2 hours. Colour scale 28-40 m water depth. Inset (bottom): HISAS image rendered on top of HISAS bathymetry from a 50 x 50 m section centred at 75 m range, showing coral reefs and sand waves.

interferometric SAS survey systems. The many benefits of using SAS shown here warrant adaptation of these processing chains to the new quality of data that interferometric SAS systems can provide. ~

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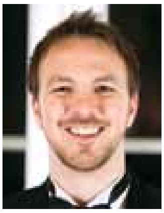

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